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Multi-criteria evaluation of parabolic trough collector with internally finned absorbers

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HIGHLIGHTS

- Twelve different internally finned absorbers are examined in the LS-2 PTC.
- The thermal enhancement and the pressure drop are the main calculated parameters.
- Four evaluation criteria are used for determining the optimum fin geometry.
- The fin with 10 mm length and 2 mm thickness is found to be the optimum case.
- The optimum fin presents 0.82% thermal efficiency enhancement compared to smooth case.

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ABSTRACT

Among the solar concentrating technologies, parabolic trough collector (PTC) is the most mature and cost-effective technology for medium and high-temperature levels (150–400 °C). This paper investigates the utilization of internally finned absorbers in LS-2 PTC module for various operating conditions. Twelve different longitudinal fins are tested and compared with the smooth case. The analysis is performed with SolidWorks Flow Simulation, using a validated model by literature results. Generally, it is proved that both greater length and thickness lead to higher thermal enhancement and to higher pressure losses. Various methods are presented for evaluating together the thermal efficiency or Nusselt number enhancement versus the increase in pressure drop or in the friction factor. Taking into consideration four different criteria, the absorber with 10 mm fin length and 2 mm fin thickness is found to be the overall optimum case. For this case, the thermal efficiency is enhanced about 0.82%, the Nusselt number increase 65.8%, while the friction factor and the pressure losses are about the double compared to the smooth case.

1. Introduction

Solar energy exploitation is vital in order to face the recent energy problems which are the climate change, the fossil fuel depletion, the high energy consumption and the increasing electricity price [1–3]. Solar energy is the most promising renewable technology because this energy source is able to be used in numerous applications and it has great availability [4]. The most usual applications which exploit the solar energy are space heating/cooling, industrial heat production and electricity production [5–8].

The last years, a lot of research has been focused on the development and improvement of Concentrating Solar Power Plants (CSP) because these technologies are able to produce high amounts of electricity in rural and other areas with a reasonable installation cost [9,10]. Parabolic trough collector (PTC) is the most mature and cost-effective technology for utilization in CSP Plants and there is a great experience on this solar technology [11,12]. Their specific cost is about 200 €/m^2 which is a relatively low value compared to other solar concentrating technologies.

The PTC is an imaging concentrating solar collector which usually produces heat at medium and high temperatures (150–400 °C) [13] with relatively high thermal efficiencies (50–70%) [14]. The usual working fluids in PTCs are thermal oils as Dowtherm A, Syltherm 800, Therminol VP-1, Therminol D12 and Sandotherm for temperatures up to 400 °C [15]. Moreover, there are applications which use water/steam as working fluid, but in these applications, there is also need for high-pressure levels in the collector loop, as well as there are difficulties in the control strategy of the system [9]. The last years, the use of molten salts (mainly nitrate salts) is usually examined because these working fluids are able to operate up to 550–600 °C leading to higher

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Nomenclature

A	area, m^2
C	concentration ratio, –
c_p	specific heat capacity under constant pressure, J/kg K
D	diameter, m
F	focal length, m
f	friction factor, –
F_I	objective function for thermal efficiency and pressure drop, –
F_{II}	objective function for Nusselt ratio and friction factor ratio, –
G_b	solar direct beam irradiation, W/m^2
h	heat transfer coefficient, W/m^2 K
h_{out}	convection coefficient between cover and ambient, W/m^2 K
k	thermal conductivity, W/m K
L	tube length, m
m	mass flow rate, kg/s
Nu	Nusselt number, –
Q	heat flux, W
Re	Reynolds number, –
r	concentrator reflectance, –
t	fin thickness, mm
P_{out}	outlet pressure, bar
p	fin length, mm
T	temperature, K
T_{sky}	sky temperature, K
u	fluid velocity, m/s
V	volumetric flow rate, L/min
V_{wind}	ambient air velocity, m/s
W	width, m

Greek symbols

α	absorber absorbance, –
ε	emittance, –
ΔP	pressure drop, kPa
η_I	efficiency enhancement index for the same pumping work, –
η_{II}	efficiency enhancement index for the same pressure drop, –
η_{opt}	optical efficiency, –
η_{th}	thermal efficiency, –
θ	solar incident angle, °
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
τ	cover transmittance, –
φ	peripheral absorber angle, °

Subscripts and superscripts

a	aperture
am	ambient
c	cover
ci	inner cover
co	outer cover
fm	mean fluid
in	inlet
loss	thermal loss
max	maximum
min	minimum
out	outlet
r	receiver
ri	inner receiver
ro	outer receiver
s	solar
th	theoretical
u	useful
w	pumping work
0	reference/smooth case

Abbreviations

CFD	computational fluid dynamics
LCR	local concentration ratio
PTC	parabolic trough collector

thermodynamic efficiencies in the CSP Plants [16]. However, the utilization of these working fluids is limited because of freezing problems which damage the components of the system (valves, pumps and ball-joints) [17]. The need for operation in higher temperature levels has made the researchers examine alternative working fluids as liquid sodium for temperatures up to 800 °C and gas working fluid (air, nitrogen, carbon dioxide and helium) for temperatures up to 1000 °C [18,19]. Nevertheless, the utilization of these working fluids is not guaranteed and their examination is in the preliminary stage for now [20].

As it is stated before, among the possible solutions for working fluids in PTCs, the use of thermal oils seems to be one of the most usual and reliable choices. These working fluids operate with a safety up to 400 °C under low-pressure levels (usually close to 15 bar) [21]. This temperature limit creates limitations in the thermodynamic efficiency of the power cycle, a critical fact which is associated with the financial sustainability of CSP Plants with PTCs [9]. Thus, a lot of research has been focused on ways which enhance the thermal performance of PTCs [9,11].

The main concept of the examined ideas for enhancing the thermal performance is to increase the heat transfer coefficient between the absorber and the fluid. This situation leads to lower absorber temperature and to lower thermal losses which finally make the thermal efficiency to be higher [22]. One solution, which is extensively examined in the literature, is the utilization of nanofluids as working fluids [23]. These fluids are created by dispersing metallic nanoparticles as Fe, Al, Cu, Fe_2O_3, Al_2O_3, CuO, TiO_2 and SiO_2 inside a base fluid (usually water or thermal oil) [24]. The final mixture (nanofluid) presents higher thermal conductivity and density, two factors which enhance the thermal performance of the system. In literature, there are numerous studies which examine the utilization of water and thermal oil-based nanofluids in PTCs [25–30] and they generally prove enhancements up to 4%. However, the high cost of the nanofluids, the high preparation needs, the agglomeration problems and the need of higher quality equipment (pumps and valves) make them a not reliable solution at this time [31,32].

The next part of literature studies associated with the thermal enhancements in PTCs examines geometrical improvements on the absorber. Two are the main strategies; the use of internally modified absorber and the use of inserts in the flow. Both of these techniques try to increase the effective conductivity of the fluid and to increase the Nusselt number. This increase is able to enhance the thermal efficiency and to improve the collector's performance. However, the relatively high-pressure drop due to the increase of turbulence in the fluid is a problem which has to be taken into account in all these cases.

An extra advantage of the thermal enhancement inside the flow of the absorber is the decrease of deformation problems in the absorber and in the glass cover. The non-uniform heat flux distribution over the absorber creates high-temperature gradients [33] which increase the